Accepted for publication in *The Astrophysical Journal*

The Size of the Extragalactic Source J1801−231 and the Association of Pulsar PSR B1758−23 with the Supernova Remnant W 28

M. J Claussen[1], W. M. Goss[1], K. M. Desai[2], and C. L. Brogan[1]

ABSTRACT

We have used the NRAO Very Large Array (VLA) in conjunction with the Very Long Baseline Array (VLBA) Pie Town antenna as a real-time interferometer system to measure the size of the extragalactic source J1801−231 as a function of frequency from 1285 to 4885 MHz. These observations were made in an attempt to determine the effect interstellar scattering has on the observed sizes of OH (1720 MHz) masers in the nearby (d = 2.5 kpc) supernova remnant W 28.

The observations clearly show that J1801−231 displays angular broadening due to turbulence in the Galaxy's interstellar medium. The minimum distance of the nearby (two arcminutes from J1801−231) pulsar PSR B1758−23 is constrained to be 9.4±2.4 kpc. This value is based on both the measured size of 220 mas for J1801−231 at 1715 MHz and the temporal broadening of the pulsar. A single thin scattering screen along the line of sight to the W 28 OH(1720 MHz) masers must be at 4.7±1.2 kpc for this minimum pulsar distance. The screen may be placed closer to the Earth, but for reasonable values of the pulsar distance (i.e., the pulsar is within the Galaxy), this choice leads to a negligible scattering contribution to the sizes of the masers.

Thus the OH(1720 MHz) masers, at a distance of 2.5±0.7 kpc, are unaffected by interstellar scattering, and the measured maser sizes must be intrinsic. Our measured upper limits to the size of the pulsar itself are consistent with the distance estimates to the pulsar and the scattering screen.

Subject headings: masers — ISM: supernova remnants — scattering

[1]National Radio Astronomy Observatory (NRAO) Array Operations Center, P.O. Box O, Socorro, New Mexico 87801, USA

[2]Renaissance Technologies

1. Introduction

The W 28 supernova remnant (SNR) lies in the direction of the Galactic Center: $(l, b) = (6.8, -0.06)$. The distance to W 28 is somewhat uncertain. Since the distance to the SNR is important to the conclusions of the current study, it is useful to examine previous estimates of the distance found in the literature. Many authors have used the $\Sigma - D$ relation to derive a distance to W 28 near ∼2 kpc (Milne 1970; Clark & Caswell 1976; Goudis 1976; Milne 1979); however, as discussed by Kaspi et al. (1993), this method is extremely uncertain. The furthest distance estimated in the literature is 3.6 kpc by Lozinskaya (1974), based on Hα measurements and assuming an LSR velocity near +18 km s^{-1} for W 28. Velazquez et al. (2002) estimate a distance of 1.9±0.3 kpc adopting +7 km s^{-1} for the LSR velocity, and assuming a standard circular rotation model (this is the near kinematic distance; 15 kpc is the far kinematic distance). Frail, Kulkarni, & Vasisht (1993) adopt a distance of 3 kpc, based on HI absorption, assuming an LSR velocity of 17.6 km s^{-1}. While the weight of the evidence for distance estimates to W 28 favors a lower distance (∼ 2 kpc; the argument of Velazquez et al. 2002 for an LSR velocity of +7 km s^{-1}is especially strong), we adopt a conservative estimate for the distance to W 28 of 2.5±0.7 kpc.

The 60,000 year old pulsar PSR B1578−23 lies in the same direction as W 28 but is located outside the SNR, approximately three arcminutes to the north of its bright radio continuum edge. A radio continuum source, J1801−231 (also known as 1758−231), lies within two arcminutes of this pulsar. J1801−231 is assumed to be an extragalactic source, coincidentally along the line of sight to the pulsar, based on measurements of neutral hydrogen absorption (Frail, Kulkarni, & Vasisht 1993). Using observations of the pulsar and the neighboring extragalactic source, Frail et al. argued in favor of the association of the pulsar and the SNR. Kaspi et al. (1993) disagreed, suggesting that the pulsar was much more distant. The discussion of Frail et al. was based upon the similarity of HI absorption profiles toward the pulsar and extragalactic source. Kaspi et al. base their conclusion on the high dispersion measure of the pulsar (1074 pc cm^{-3}), and the argument that no compact HII region or cloud appears to lie along the line of sight to the pulsar which could account for such a high dispersion measure.

Several OH (1720 MHz) masers associated with the W 28 SNR (Frail, Goss, & Slysh 1994) have been studied at high angular resolution with the Very Long Baseline Array (VLBA) and MERLIN by Claussen et al. (1999a). Though there have been only a few OH(1720 MHz) masers in W 28 observed at 10 mas resolution, those masers are resolved and have sizes ranging from 50 to 100 milliarcseconds (mas). Claussen et al. discussed the effects of interstellar scattering on the sizes of the masers and the constraints that could be placed on such scattering sizes based on available information about the size of J1801−231, the pulsar, and the pulse broadening of the pulsar. Interstellar scattering of an extragalactic source results in angular broadening while interstellar scattering of a pulsar's radio emission can also result in pulse broadening, an increase in the apparent width of a pulsar's average pulse profile beyond its intrinsic width. The degree of angular broadening for the masers and the extragalactic source and the degree of pulse broadening for the pulsar all depend in different ways upon the relative geometry of the observer, scattering material, and sources. Measurements of these scattering effects can constrain the distribution of the scattering material and can be used to estimate, for example, the unscattered sizes of the masers.

In this paper, we present angular broadening measurements of the extragalactic source J1801−231 as a function of observing frequency from 1285 MHz to 4885 MHz. We used the NRAO Very Large Array (VLA) in its most extended configuration (**A**) linked, in real time, with the Pie Town (Pt) antenna of the Very Long Baseline Array (VLBA). The questions to be addressed by these measurements are (1) the relative distances of the pulsar and the supernova remnant (which we assume harbors the OH masers), (2) the effects of scattering on the observed size of the masers and the pulsar, and (3) the distance to the scattering screen.

2. Observations and Data Reduction

2.1. Observations

The VLBA Pie Town (Pt) antenna has been linked in real time via fiber-optic cable with the VLA (Claussen et al. 1999b; Beresford 2000). For purposes of scientific observations, the data from the Pt antenna is sent to the VLA correlator just like any other VLA antenna. For sources with declinations $> 40^\circ$, the angular resolution in two dimensions is improved by approximately a factor two compared with using the VLA in the **A** configuration. As the declination of sources tends to the south, the increase in resolution is realized in only one dimension.

We observed the extragalactic source J1801−231 on January 15, 2001, with the VLA+Pt link. We performed five snapshots of the source of approximately 10 minutes each on source at six frequencies: 1285, 1315, 1365, 1665, 1715, and 4885 MHz. The five snapshots covered an hour angle range of about ± 1.5 hours. At the frequencies 1285 to 1715 MHz, we employed 25 MHz front-end filters to help avoid radio-frequency interference and minimize the radial smearing due to the effects of finite bandwidth (see e.g. Bridle & Schwab 1999, and references therein). At 4885 MHz the filters were set at 50 MHz. Two independent circular polarizations were observed at each frequency, and subsequently averaged in the imaging process. The data were edited, calibrated, and imaged in the standard manner, using the NRAO Astronomical Image Processing System (AIPS). Absolute flux calibration was provided assuming that 3C 286 has flux densities of 15.44, 15.27, 15.01, 13.63, 13.43, and 7.46 Jy beam^{-1} at 1285, 1315, 1365, 1665, 1715, and 4885 MHz respectively.

Uniform weighting of the u,v data was used in the imaging to allow the data from Pt baselines to contribute to the image. The AIPS task JMFIT was used to fit two-dimensional gaussians to the brightness distribution of J1801−231, and to deconvolve the synthesized beam from those fits. Table 1 shows a summary of the observations, imaging, and gaussian fits to the images of J1801−231. Since the sizes of the radio source measured by fitting and deconvolving the observed size are nearly circular, the deconvolved sizes reported in Table 1 are the geometric mean of the two-dimensional gaussian fits. We also detected the pulsar B1758−23; the image of the pulsar suffers from severe bandwidth smearing, since it is two arcminutes from the phase center. Accurate size measurements of the pulsar are thus compromised. However, we attempted to correct the measured sizes of the pulsar by estimating the magnitude of the smearing. At all frequencies, the best estimate of the size of the pulsar is < 0.5 arcseconds.

3. Results and Discussion

Figure 1 shows the results of our angular size measurements of J1801−231: a log-log plot of the deconvolved size θ versus observing frequency. A well-known frequency scaling relation exists for the measured angular size of a source whose structure is dominated by interstellar scattering effects (Rickett 1977):

$$\theta_{scattered} \propto \nu^{\gamma} \quad ,$$

where γ takes on a value between -2 and -2.2 . For reference, we have drawn a line with slope -2 in Figure 1; it is clear that the measured sizes shown are consistent with the effects of interstellar scattering.

Under the assumption that the intervening turbulence is confined to a single thin screen, scattering measurements of galactic and extragalactic compact sources can completely constrain the location of the screen. The assumption that the scattering screen is thin is equivalent to the statement that the scattering screen has a thickness which is much less than the distance to the extragalactic source (e.g. Trotter, Moran, & Rodríguez 1998). Since the extragalactic source is likely to be at least several megaparsec away, a thickness of several pc for the screen is consistent with this assumption. Temporal broadening of the pulsed emission from a pulsar and angular broadening of pulsars and masers depend differently upon the distribution of scattering material along the line of sight. Additionally, angular broadening of the extragalactic source J1801−231 is sensitive only to the strength of the turbulence, not to its distribution along the line of sight.

In addition to the angular size measurements of J1801−231 and the pulsar PSR B1758−23 reported here, we also use the measured size of the OH masers (Claussen et al. 1999a), and the measured temporal broadening of the pulse of the pulsar (Kaspi et al. 1993; Frail, Kulkarni, & Vasisht 1993) in order to estimate 1) the distance to the pulsar, 2) the distance to the scattering screen, and 3) the unscattered size of the OH masers. In order to make these estimates, we make the further assumption that the scattering screen is uniform across both the pulsar and the extragalactic source (the two radio sources are separated by about 2 arcminutes). At a distance of 10 kpc, 2 arcminutes corresponds to about 6 pc. On pc scales, it is not unreasonable to expect that the scattering medium is at least somewhat uniform. Lazio et. al (1999) find that the Galactic center scattering region (covering Sgr A*, OH masers, and extragalactic sources) is inhomogeneous on scales of order 10 pc, whereas Fey, Spangler, & Mutel (1989) find that scattering in the Cygnus region changes by factors of two to five over angular separations of a few degrees (100—200 pc).

If we denote the measured sizes of the extragalactic source, the pulsar, and the OH(1720 MHz) masers as θ_e, θ_p, and θ_m, respectively, the distance to the scattering screen, the masers, and the pulsar as d_s, d_m, and d_p, respectively, and the temporal broadening of the pulsar as τ_p, then three relevant relations can be derived (e. g. Britton, Gwinn, & Ojeda 1998; Frail, Kulkarni, & Vasisht 1993):

$$\theta_e = \theta_p(1 + f_p) \tag{1}$$

$$\theta_e = \theta_m(1 + f_m) \tag{2}$$

$$1 + f_p = (\theta_e)^2 \; d_s/(8c \ln 2 \; \tau_p) \quad , \tag{3}$$

where

$$f_p = \frac{d_s}{(d_p - d_s)} \quad , \quad f_m = \frac{d_s}{(d_m - d_s)} \quad ,$$

and f_p and f_m are dimensionless while θ_e, θ_m, and θ_p are in radians, τ_p is in seconds, and c is the speed of light.

We can rearrange these equations to obtain:

$$\frac{\theta_p}{\theta_e} + \frac{d_s}{d_p} = 1 \tag{4}$$

$$\frac{\theta_m}{\theta_e} + \frac{d_s}{d_m} = 1 \tag{5}$$

$$\frac{d_s}{d_p} + \frac{(8c\ \ln 2\ \tau_p)}{(\theta_e^2 d_s)} = 1 \quad . \tag{6}$$

In distance units of kpc, time units of seconds, and angular units of arcseconds, Equation 6 becomes:

$$\frac{d_s}{d_p} + 2.292\ \frac{\tau_p}{(\theta_e^2\ d_s)} = 1 \tag{7}$$

and Equation 4 becomes

$$\theta_p = \frac{2.292\ \tau_p}{\theta_e\ d_s} \quad . \tag{8}$$

Measurements of the three angular sizes θ_e, θ_p, and θ_m and the broadening time τ_p, will thus lead to a determination of d_s, d_m, and d_p.

In practice, the angular sizes and the broadening time are measured at different frequencies. Since scattering quantities are frequency dependent, we must transform the measurements to a common frequency. The choice of frequency is obviously the frequency of the maser angular size measurement, 1720 MHz. The size measurement of the OH masers is subject to two different interpretations: scattering due to interstellar turbulence or large intrinsic maser sizes (Lockett et al. 1999). We therefore scale all measurements to 1720 MHz and apply the above relations at that single frequency.

Theoretically, τ_p scales with $\nu^{2\gamma}$ while $\theta_e, \theta_m, \theta_p$ scale with ν^{γ}. As mentioned earlier, γ can take on a value between -2.0 and -2.2 — the exact value used for γ will have a substantial effect on the derived quantities. Uncertainties in the measurement of the sizes and the pulse broadening, along with the uncertainty in γ, lead to a range of possible estimates of the distances to the pulsar and the scattering screen and the size of the pulsar.

Although there is considerable uncertainty as mentioned above, a clear result can be obtained if we consider the direct measurement of the size of J1801−231 at 1715 MHz (θ_e =220 mas). A plot of the distance to the pulsar vs the distance to the scattering screen, using this value for θ_e in Equation 7 is shown in Figure 2. The pulse broadening time τ_p in Equation 7, necessary for the plot, was estimated by Frail et al. to be 0.07 seconds at 1670 MHz. The 1520 MHz pulse profile in Kaspi et al. is consistent with a slightly smaller 1670 MHz value in the range 0.055 to 0.057 seconds. Both of these measurements taken together would suggest a value for τ_p at 1720 MHz in the range 0.048 to 0.051 seconds. In our analysis we find that there are no significant differences in our conclusions using this range of values for τ_p. The plot in Figure 2 uses the mean of pulse broadening times, 0.0495 seconds. Dashed lines in Figure 2 show the same relation for pulsar distance — screen distance for $\theta_e = 180$ and $\theta_e = 260$ mas. For $\theta_e = 220$ mas, Figure 2 shows a clear minimum for the pulsar distance of about 9.4 kpc, which requires the scattering screen to be at a distance of 4.7 kpc. The SNR distance of 2.5 kpc is also plotted on Figure 2, for reference.

The solid line in Figure 2 is determined directly from Equation 7 with $\tau_p = 0.0495$ seconds and $\theta_e = 220$ mas, so we can analytically determine where the minimum pulsar distance occurs. Equation 7 can be written as a quadratic equation in d_s,

$$d_s{}^2 - d_p d_s + \beta d_p = 0 \quad , \tag{9}$$

where

$$\beta = 2.292 \frac{\tau_p}{\theta_e{}^2} \quad .$$

The solutions (for d_s) to this quadratic equation are

$$d_s = \frac{d_p \pm \sqrt{d_p^2 - 4\beta d_p}}{2} \quad . \tag{10}$$

We can determine a minimum value for d_p by taking the derivative $\frac{dd_p}{dd_s}$. This leads to the well-known relation

$$d_{p,min} = 2d_s$$

(e.g. Gwinn, Bartel, & Cordes 1993). This minimum value of d_p occurs when $d_p = 4\beta$ and $d_p = 0$. Since $d_p = 0$ is not an acceptable solution, we find that the minimum value for d_p is 4β. Table 2 lists a few values for $d_{p,min}$ and the value of d_s where $d_{p,min}$ occurs, using values of θ_e which bracket the errors of our measurements. The entries in Table 2 show that, even for values of θ_e outside our one-sigma errors, the minimum distance for the pulsar is well beyond the distance to the W 28 SNR. Based on these values in Table 2, we can estimate the uncertainty in the minimum pulsar distance to be ± 2.4 kpc, with a corresponding uncertainty in the screen distance to be ± 1.2 kpc.

With an estimate of the minimum distance to the pulsar and a corresponding distance to the screen established, we can use Equation 8 to estimate the scattered size of the pulsar. This estimate is 110 ± 15 mas at 1720 MHz, well below our upper limit for the size of the pulsar. Table 2 also lists the values of the pulsar scattered sizes (θ_p) for different values of θ_e.

It is clear from Figure 2 that smaller values of the screen distance are possible for a given value of θ_e, as the pulsar distance increases (to the left of the minimum pulsar distance in Figure 2). We can use the solid curve in Figure 2, in conjunction with Equation 2, to estimate the size of the OH(1720 MHz) masers (θ_m), based on an extreme value for the pulsar distance. Selecting a pulsar distance of 15 kpc, the screen distance would have to be 2.9 kpc, and thus the ratio of the extragalactic source size to the maser source size $(1 + f_m)$ would be $\sim$33, predicting a maser scattering size of < 7 mas. Placing the screen closer to the Earth along the line of sight (in order to decrease f_m and increase the scattering size of the masers) requires that the pulsar be even more distant, likely outside the Galaxy.

These estimates for the distances of the scattering screen and the pulsar have two immediate ramifications: (1) the pulsar is *not* associated with the W 28 SNR; and (2) the OH(1720 MHz) masers are unscattered, since placing the screen at 4.7 kpc puts it beyond the distance to the supernova remnant (2.5 kpc). Thus the measured angular sizes of the W 28 masers as reported by Claussen et al. (1999a) (50 — 100 mas) are intrinsic to the maser rather than due to interstellar scattering. Finally, our estimate of the distance to the pulsar is more consistent with the dispersion measure of the pulsar as measured by Kaspi et al. (1993) than with a closer distance ($d > 9.5$ kpc).

4. Conclusions

We have measured the size of the extragalactic source J1801−231 at six frequencies, and find that our size measurements are consistent with angular broadening due to turbulence in the interstellar medium. Together with the size measurements of OH(1720 MHz) masers, assumed to be associated with the W 28 supernova remnant (Claussen et al. 1999a), and the temporal broadening of the pulsar B1758−23 (Frail, Kulkarni, & Vasisht 1993; Kaspi et al. 1993), the results of the new size measurements of J1801−231 imply:

• The minimum distance for the pulsar is 9.4±2.4 kpc and it is *not* associated with the SNR. The distance to a single scattering screen for this minimum pulsar distance is 4.7±1.2 kpc, and is also beyond the SNR.

• The scattering screen can be moved placed closer to the Earth by increasing the pulsar distance. Even with an extreme distance to the pulsar, this leads to a negligible scattering contribution to the size of the OH masers.

• In either of the two possibilities above, the maser sizes must be little affected by interstellar scattering, and the sizes measured for the masers must therefore be intrinsic to the masers.

• When the pulsar is placed at the minimum distance of 9.4 kpc, the scattering size of the pulsar, estimated from the J1801−231 size measurements, is about 110 mas at 1720 MHz, consistent with our upper limit to the pulsar size of 500 mas.

We thank Walter Brisken for estimating the size of the pulsar in the presence of bandwidth smearing, and we also thank an anonymous referee for a careful reading of the manuscript and suggestions which improved the paper. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

Beresford, R., 2000, VLA Technical Reference No. 77

Bridle, A. H., and Schwab, F. R. 1999, in Synthesis Imaging in Radio Astronomy II, eds. G. B. Taylor, C. L. Carilli, and R. A. Perley, A.S.P. Conference Series, 180, 371.

Britton, M. C., Gwinn, C. R., & Ojeda, M. J. 1998, ApJ, 501, L101.

Clark, D. H. & Caswell, J. L. 1976, MNRAS, 174, 267

Claussen, M. J, Goss, W. M., Frail, D. A., & Desai, K. M. 1999, ApJ, 522, 349.

Claussen, J. J, Beresford, R., Sowinski, K., & Ulvestad, J. S. 1999 BAAS, 31, 83.05.

Fey, A. L., Spangler, S. R., & Mutel, R. L. 1989, ApJ, 337, 730

Goudis, C. 1976, Ap. & Sp. Sc., 45, 133

Frail, D. A., Kulkarni, S. R., & Vasisht, G. 1993, Nature, 365, 136

Frail, D. A., Goss, W. M., & Slysh, V. I. 1994, ApJ, 424, L111

Gwinn, C. R., Bartel, N., & Cordes, J. M. 1993, ApJ, 410, 673

Kaspi, V. M., Lyne, A. G., Manchester, R. N., Johnston, S., D'Amico, N., & Shemar, S. L. 1993, ApJ, 409, L57

Lazio, T. J. W., Anantharamaiah, K. R., Goss, W. M., Kassim, N. E. & Cordes, J. M. 1999, ApJ, 515, L196

Lockett, P., Gauthier, E., & Elitzur, M. 1999, ApJ, 511, 235.

Lozinskaya, T. 1974, Soviet Astron. 17, 603

Milne, D. K. 1970, Austr. Journal of Physics, 23, 425

Milne, D. K. 1979, Austr. Journal of Physics, 32, 83

Rickett, B. J., 1977, ARA&A, 15, 479

Trotter, A. S., Moran, J. M., & Rodríguez, L. F. 1998, ApJ, 493, 666

Velazquez, P. F., Dubner, G. M., Goss, W. M., & Green, A. J. 2002, ApJ, in the press.

AAS LaTeX macros v5.0.

Table 1: Summary of Observations of J1801−231

Frequency (MHz)	Beam (mas)	$\theta_{J1801-231}$ (mas)	Total Flux Density (mJy)
1285	2660 × 1290[1]	580±150	54.8
1315	2360 × 680	475±40	56.2
1365	2140 × 660	500±40	59.6
1665	1800 × 560	310±40	51.2
1715	1770 × 540	220±40	45.5
4885	650 × 280	<90	23.6

[1] VLA only.

Table 2: Derived values of minimum pulsar distance, screen distance at which the minimum pulsar distance occurs, and the pulsar size for this screen distance.

θ_e(mas)	$d_{p,min}$(kpc)	d_s(kpc)	θ_p(mas)
180	14.0	7.0	90
200	11.4	5.7	100
220	9.4	4.7	110
260	6.7	3.4	130
300	5.0	2.5	150

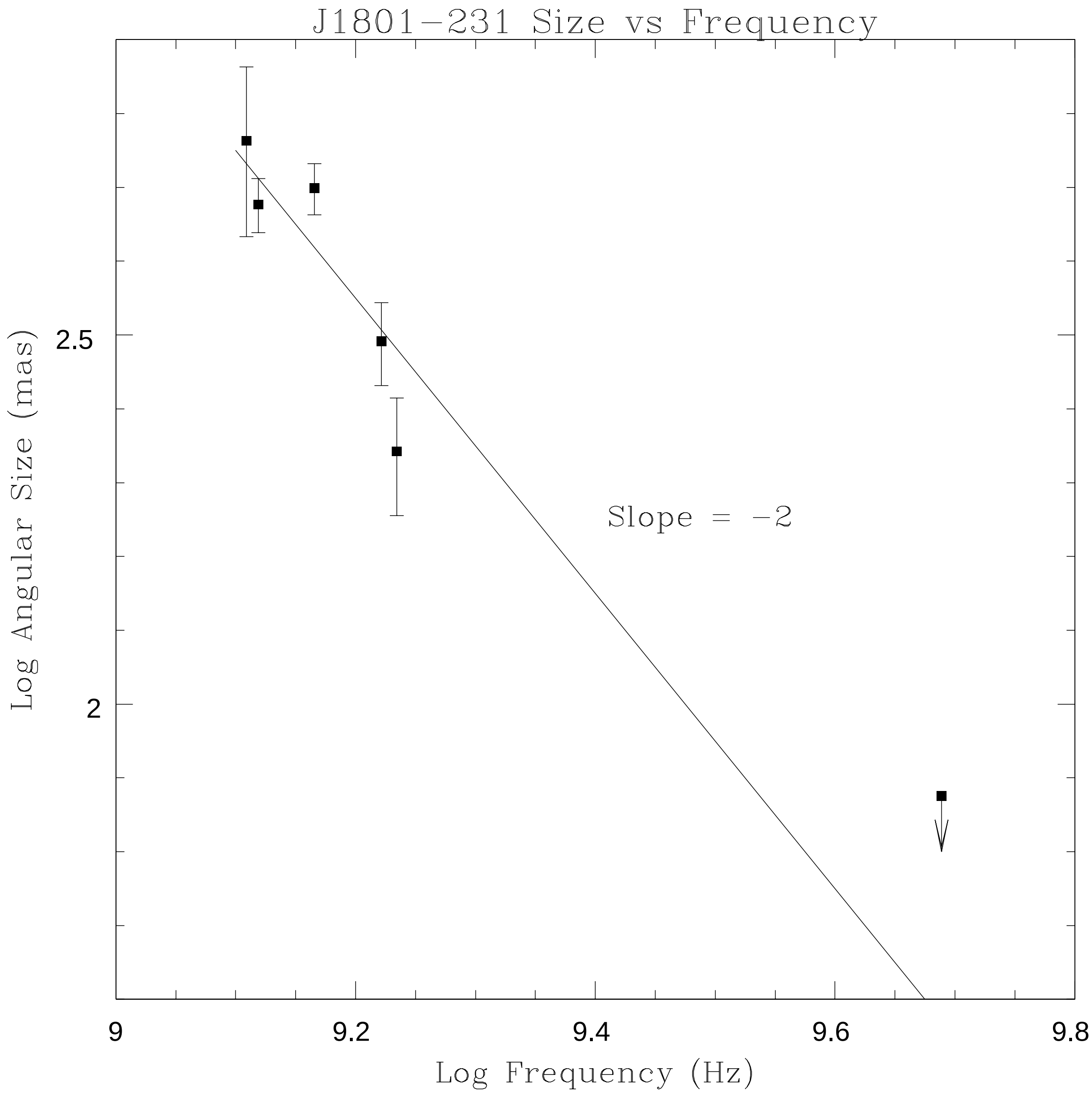

Fig. 1.— A log-log plot of the measured size of the extragalactic source J1801−231 vs the observing frequency. The size of the source at 4885 MHz (the point at the far right) is an upper limit. The solid line is a line with slope −2; it is *not* a fit to the data points.

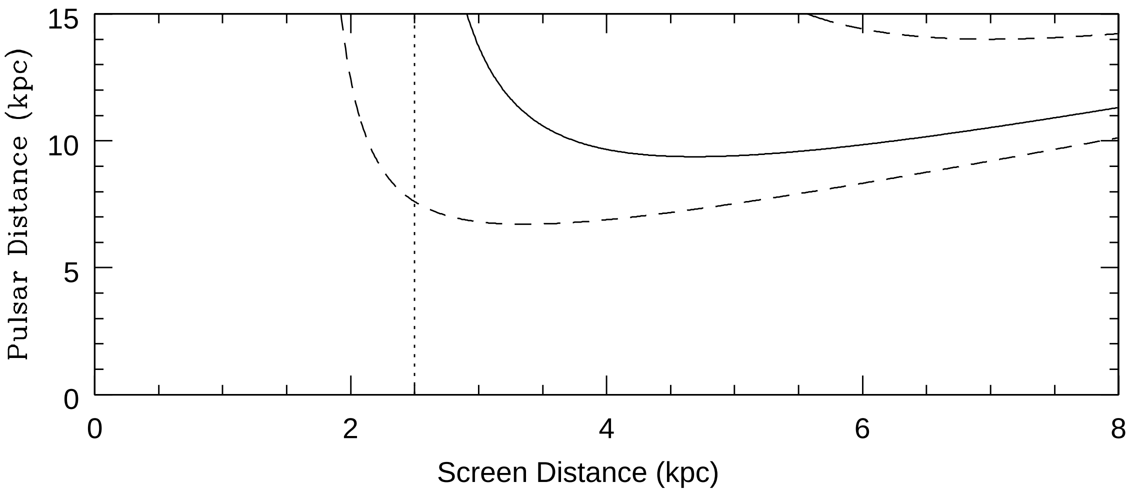

Fig. 2.— Plot of the distance to the pulsar B1758−23 vs. a single scattering screen's distance based on Equation 7. The solid line assumes a scattering size for J1801−231 to be 220 mas at 1715 MHz, and the pulsar temporal broadening is assumed to be 0.0495 seconds. The dashed lines show pulsar distance - screen distance relations for the scattering size of J1801−231 of 180 mas (upper curve) and 260 mas (lower curve). The dotted line shows the assumed distance to the W 28 supernova remnant.